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# Future prospects of Super-Kamiokande and Hyper-Kamiokande

Masayuki Nakahata

*Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo*

*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo*

**Abstract**

The Super-Kamiokande detector has been obtaining data since 1996 and has produced many important physics results, including measurements of oscillations in atmospheric, solar and accelerator neutrinos. This paper discusses the prospects for Super-Kamiokande over the next 10 years and the capabilities of the next-generation experiment, Hyper-Kamiokande. Indeed, the T2K and reactor neutrino experiments have established that the mixing angle $\theta_{13}$ is relatively large, and therefore measurements of the CP phase using a large scale accelerator neutrino experiment such as Hyper-Kamiokande are possible. In addition, since Hyper-Kamiokande is a multi-purpose detector, studies of the mass hierarchy using atmospheric neutrinos, searches for proton decay and measurements of astrophysical neutrinos can also be performed.


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*Keywords:* neutrinos, Super-Kamiokande, Hyper-Kamiokande

## 1. Introduction

Super-Kamiokande (SK) is a 50-kton water Cherenkov detector that has 11,000 20-inch-diameter photomultipliers (PMTs) as its inner detector and 1,885 8-inch-diameter PMTs as its outer detector. A schematic of the detector is shown in Fig.1. Data collection by SK started in April 1996. Oscillations of atmospheric neutrinos were discovered in 1998 [1], thereby demonstrating that neutrinos have a non-zero mass. In 2001, accurate measurements of the $^{8}$B solar neutrino flux by SK and the Sudbury Neutrino Observatory (SNO) revealed that neutrino oscillations explain the solar neutrino problem [2, 3]. Since these discoveries, precise measurements of atmospheric and solar neutrinos have been performed, unraveling various aspects of neutrino oscillations, such as the $L/E$ dependence of atmospheric neutrinos [4] and the day/night difference in the solar neutrino flux [5].

SK has been used as a far detector in long-baseline neutrino experiments. The K2K experiment, conducted from 1999 to 2004, used a wideband neutrino beam produced by a 12-GeV proton accelerator at KEK, and confirmed the $\nu_\mu$ disappearance [6]. The T2K experiment, using an intense neutrino beam from the J-PARC accelerator, begun in 2009. The appearance of electron neutrinos (associated with a mixing angle $\theta_{13}$) and high precision measurements of the oscillation parameters are the principal goals. The first indication of the appearance of electron neutrinos was found in June 2011, and it was upgraded to the discovery level in 2012.

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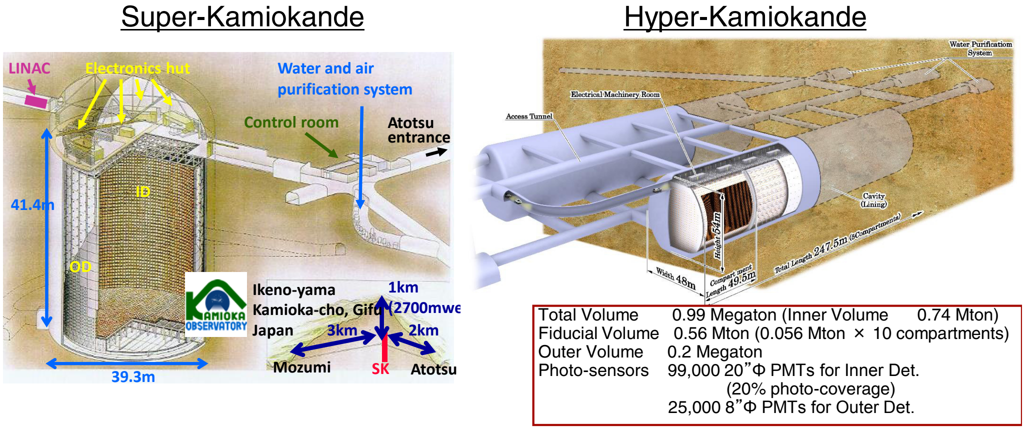


Fig. 1. Schematic views of the Super-Kamiokande and the Hyper-Kamiokande detectors.

SK has contributed to the discovery of neutrino oscillations and has determined all known oscillation parameters thus far. It is still the world largest detector for neutrinos ranging from a few MeV to tens of GeV in energy. The measured value of $\theta_{13}$ was relatively large, namely $\sin^2(2\theta_{13}) =\sim 0.1$, and therefore measurements of the CP phase by comparing neutrino and anti-neutrino oscillations are possible using beams from proton accelerators. However, a larger target mass is necessary for this purpose. Correspondingly, a 1-Mton water-based Cherenkov detector, referred to as Hyper-Kamiokande, has been proposed. In this paper, future prospects for both SK and HK are discussed.

## 2. SK data in the next decade

The number of atmospheric neutrino events observed so far is about 38,000 and this is expected to increase at a rate of about 3,200 per year, counting both fully contained (FC) and partially contained (PC) events. Because of the influence of the matter effect on neutrino oscillations in the Earth, the mass hierarchy, i.e., whether $\Delta m^2_{32} = m^2_3 - m^2_2$ is positive or negative, affects the excess number of upward-going multi-GeV electron-like events. The excess depends on the value of $\theta_{23}$ and on the absolute value of $\Delta m^2_{32}$. The accuracy to which these values are known will improve as data collection by T2K progresses. It is expected that the mass hierarchy will be known to the $2\sigma$ level after about 10 more years of atmospheric neutrino measurements, assuming that $\sin^2\theta_{23}$ is equal to about 0.6. An octant of $\theta_{23}$ will be determined at the 2.1 to 2.6 $\sigma$ level if $\sin^2\theta_{23}$=0.4/0.6.

The neutrino oscillation parameters $\theta_{12}$ and $\Delta m^2_{12}$ have been determined by solar neutrino experiments (Homestake, Kamiokande, SAGE, GALLEX/GNO, SK, SNO, and Borexino) and the KamLAND reactor neutrino experiment. Low-energy solar neutrinos (below 1 MeV) exhibit vacuum oscillations, whereas higher-energy solar neutrinos are affected by matter. The transition from vacuum to matter oscillations should be observable in the $^8$B spectrum, although it has not yet been found. The energy threshold of the SK solar neutrino analysis has been lowered to 3.5 MeV (in kinetic energy) for the SK-IV phase (since September 2008) by reducing the radon background in the detector. However, the fiducial mass for energies below 5 MeV is almost half the nominal value of 22.5 kton, because a radon background still remains in the lower part of the detector. After reducing this background, precise $^8$B spectra will be collected in the next 10 years. A spectrum upturn at about the 3 $\sigma$ level should be observed within the next 10 years.

If a supernova occurs in our galaxy, many thousands of neutrino events are expected to be detected at SK. Most of those events would be due to inverse beta reactions ($\bar{\nu}_e + p \rightarrow e^+ + n$). Hundreds of electron scattering events ($\nu + e \rightarrow \nu + e$) would also occur, and they would indicate the direction of the supernova. SK is the only detector that gives directional information.

With ten more years of SK data, estimates of the nucleon lifetime will be improved to $\sim 2.4\times10^{34}$ years for the $p \rightarrow e^+\pi^0$ decay mode and $\sim 9\times10^{33}$ years for the $p \rightarrow \bar{\nu} + K^+$ decay channel. With respect to

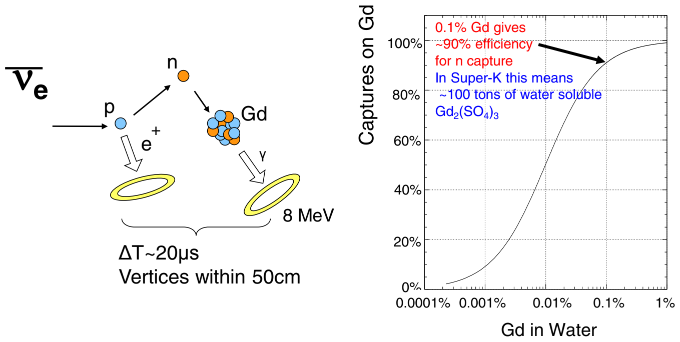


Fig. 2. Neutron tagging with gadolinium (left panel), and capture efficiency plotted as a function of Gd concentration (right panel).

the indirect search for dark matter, SK has a higher sensitivity for low-mass weakly interacting massive particles (WIMPs) than the IceCube and ANTARES detectors, because SK is highly efficient at detecting GeV neutrinos. After another decade, SK will have a sensitivity of $\sim 8\times10^{-41}$cm$^2$ and $\sim 2\times10^{-42}$cm$^2$ for spin-dependent (SD) and spin-independent (SI) interactions, respectively, of WIMPs with a mass of 10-GeV for the $\chi\chi \rightarrow \tau^+\tau^-$ channel.

## 3. R&D for the Gadolinium Project

SK has searched for neutrinos from old supernovae, known as supernova relic neutrinos (SRNs). The SRN signal is a diffuse neutrino background originating from all past supernovae. This signal has not been detected, but it is expected to lie in the 10-30 MeV energy range, in the gap between the energy of reactor and atmospheric neutrinos. So far, the search has been limited to energies above 16 MeV because of the cosmic-ray induced background. In addition, the "invisible muon background", due to electrons produced by decay of muons with energies below the Cherenkov threshold, produced by atmospheric neutrinos, is significant above 16 MeV. Nevertheless, SK has obtained an upper limit of between 2.8 and 3.1 $\bar{\nu}$ cm$^{-2}$s$^{-1}$ to be placed on the flux, with a total positron energy above 16 MeV, i.e., more than 17.3 MeV for $E_\nu$ [7], which is within a factor of 2~5 of the model predictions.

At present, the SK detector can detect only positrons efficiently, but if it could detect neutrons then the background constraining the SRN search would be greatly reduced. Such a reduction could be attained via coincidence detection of positrons and neutrons (in space using vertices spanning ~50 cm, and in time using neutron capture delayed by ~20 $\mu$s). By adding 0.2% gadolinium sulfate into the water tank, this goal can be achieved [8] as shown in Fig. 2. Gadolinium has a thermal neutron capture cross section of 49,000 barns (about 5 orders of magnitude larger than that of protons) and emits a gamma cascade of 8 MeV that can be detected by SK, i.e., using Cherenkov light. In order to obtain a 90% efficiency for neutron capture, the Gd concentration should be 0.1%, or 0.2% if $Gd_2(SO_4)_3$ is used, as demonstrated by the graph in Fig. 2. Figure 3 plots the number of SRN events expected during 10 years of SK observations using Gd neutron tagging for various effective electron-antineutrino temperatures when a supernova occurs. Astrophysical uncertainties, such as the star formation rate and the initial mass function, are listed in the figure. About 10-50 events are expected, depending on the details of the models.

In order to study the effect of dissolving Gd in the SK tank, an R&D project called EGADS (Evaluating Gadolinium's Action on Detector Systems) has been running in the Kamioka mine. The EGADS project was funded in 2009, and since then, a new 2500-m$^3$ hall near the SK detector has been excavated and a 200-m$^3$ stainless steel tank with ancillary equipment has been constructed (Fig. 4). The idea is to mimic the SK conditions inside the 200-m$^3$ tank. The tank is equipped with a selective water filtration system that removes impurities while retaining the Gd, a 15-m$^3$ Gd premixing and pretreatment plastic tank, and a device to measure the water attenuation length (called UDEAL).

From February 6 to April 20 2013, the 200-m$^3$ tank was stepwise loaded with Gd until the final 0.2% concentration was attained. Each batch was added to the 15-m$^3$ tank and then stirred until completely

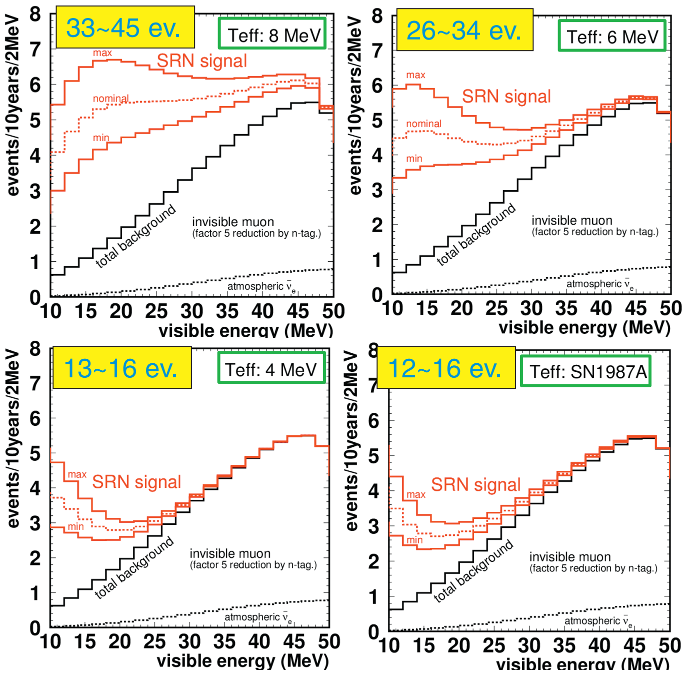


Fig. 3. Expected energy spectra for SRN search with neutron tagging using gadolinium. A 10-year data collection time is assumed. Each figure shows the spectrum for a different model of the effective $\bar{\nu}_e$ temperature. The solid red histograms show the magnitude of astrophysical uncertainties due to the stellar formation rate and the initial mass function.

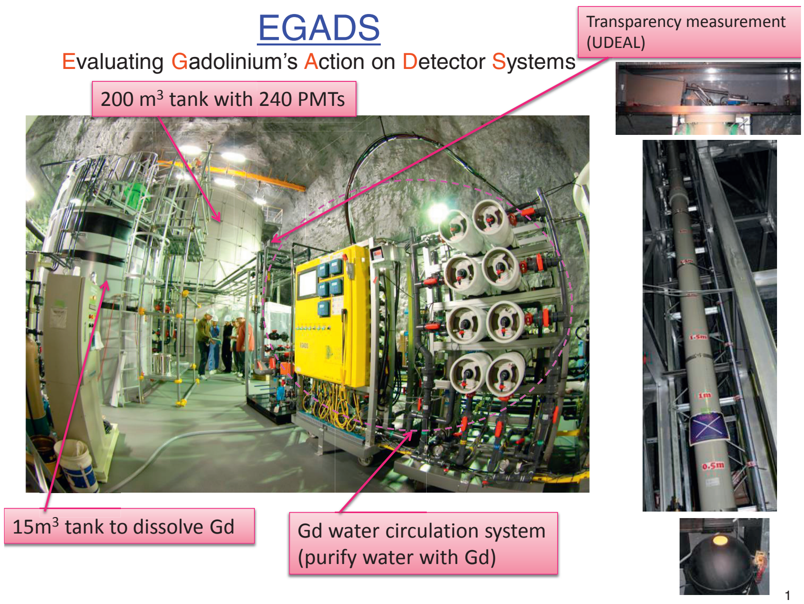


Fig. 4. Photographs of the 15-m$^3$ Gd premixing and pretreatment tank, the selective filtration system, and the 200-m$^3$ tank.

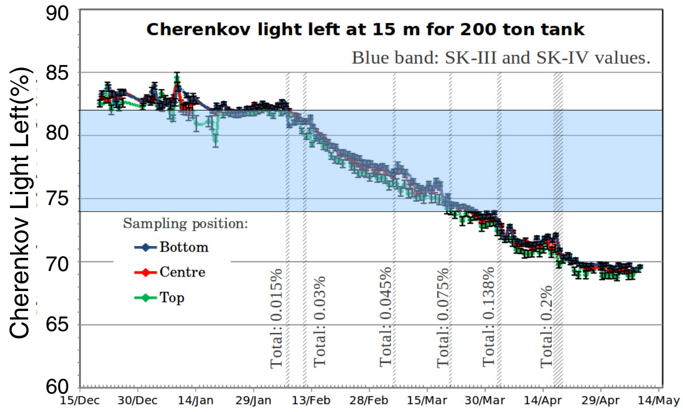


Fig. 5. Cherenkov light at 15-m depth for gadolinium-loaded water in the 200-m$^3$ tank. The horizontal blue bands are the values for SK-III and SK-IV. The vertical lines plot the injection dates, labeled by the concentrations in mass%.

dissolved. The loaded water was then circulated through the pretreatment system (with 0.2-$\mu$m and 0.3-$\mu$m filters) to remove dust and other impurities originating from the $Gd_2(SO_4)_3$. Finally, the mixed water was injected into the 200-m$^3$ tank after being processed at least once through the main water system. After the $Gd_2(SO_4)_3$ was homogeneously dissolved in the 200-m$^3$ tank, good water quality was maintained, as demonstrated in Fig. 5. This dissolution test was performed before mounting the PMTs to measure the effect of the Gd in the stainless steel tank. In the summer of 2013, 240 PMTs were installed in the 200-m$^3$ tank. Most are 20-inch PMTs of the same type used in the SK tank. The same cabling and waterproofing are also used. Several of the tubes are prototype 8-inch hybrid photodetector PMTs specially developed for Hyper-Kamiokande. Since PMT installation, pure water has been continuously circulating through the detector, and soon the Gd effect will be tested using the PMTs.

## 4. The T2K experiment

T2K is a long-baseline neutrino oscillation experiment, employing a high-intensity muon neutrino beam traveling from the J-PARC facility in Tokai to SK, a distance of 295 km. The primary goal of T2K is to measure $\theta_{13}$ by detecting the appearance of electron neutrinos, along with precision measurements of both $\Delta m^2_{32}$ and $\sin^2\theta_{23}$ via muon neutrino disappearance studies.

To produce the T2K neutrino beam, 30-GeV protons are extracted from the J-PARC main-ring accelerator and then collided with a graphite target. Charged particles produced by the collisions are sign selected and focused into the 96-m-long decay volume by three magnetic horns pulsed at 250 kA. Neutrinos are primarily produced in the decays of charged pions and kaons. T2K is the first long-baseline experiment adopting the off-axis technique, in which the neutrino beam is purposely directed at a 2.5° angle with respect to the baseline connecting the proton target and the SK far detector. This technique enables energy selection of the neutrinos, producing a narrowband muon neutrino beam whose energy peaks at the first oscillation maximum, $E_\nu$=~0.6 GeV.

In 2011, the T2K experiment reported the first clear indication of a nonzero value of $\theta_{13}$ by detecting the appearance of electron neutrinos due to $1.43\times10^{20}$ protons on target (POT) [9]. Through April 2013, $6.393\times10^{20}$ POT have been accumulated and 28 electron neutrino appearance events have been observed, while the expected number of background events was 4.92±0.55. This result corresponds to a 7.3$\sigma$ confidence level for a non-zero value of $\theta_{13}$ [10].

The beam power has reached 235 kW so far, and there are plans to increase it to 750 kW. The intention is to accumulate $7.8\times10^{21}$ POT by 2020, which is more than ten times the current amount of data. Figure 6 shows the sensitivity to $\sin^2(2\theta_{13})$ and $\delta_{CP}$ with the full data, plotted for a solution of $\delta_{CP} = -90°$, $\sin^2(2\theta_{13})$=0.1, and normal hierarchy (NH). The figure shows two cases of the beam run schedule, one for

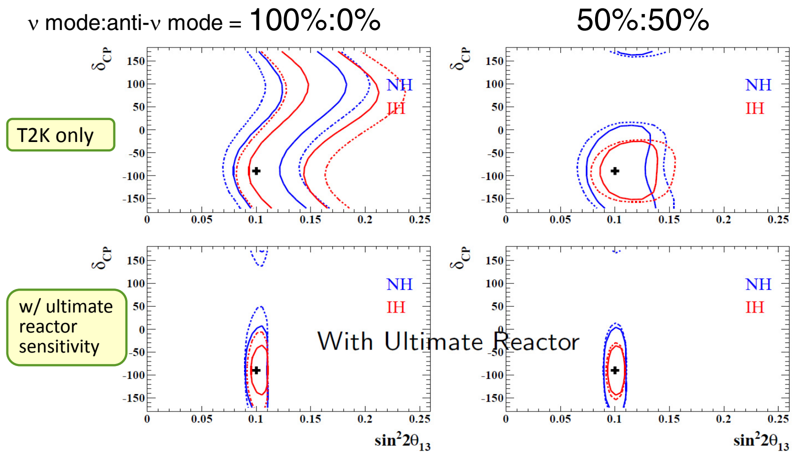


Fig. 6. Sensitivity of T2K for $\sin^2(2\theta_{13})$ and $\delta_{CP}$ at $7.8 \times 10^{21}$ POT (expected full data). A solution having $\delta_{CP} = -90°$ and $\sin^2(2\theta_{13})$=0.1 is assumed. The blue and red curves show the allowed regions assuming normal hierarchy (NH) and inverted hierarchy (IH), respectively. The solid and dashed curves are without and with current systematic errors, respectively.

a 100% $\nu$ beam (left graphs) and the other for a mixed beam with 50% $\nu$ and 50% $\bar{\nu}$ (right graphs). The upper and lower panels plot contours for the T2K data alone and for the ultimate reactor data sensitivity, respectively.

## 5. Hyper-Kamiokande

As seen in Fig. 6, the T2K experiment may be capable of obtaining a hint for a finite CP phase, but an order of magnitude more events are necessary before a firm conclusion can be reached. For that purpose, a much larger detector is needed. Hyper-Kamiokande (HK)[11] is a 0.99-Mton water Cherenkov detector, and its fiducial mass of 0.56 Mton is 25 times larger than that of SK. A schematic of the HK detector is presented in Fig. 1. The detector consists of two tunnels, each of which is optically subdivided into five compartments. There are both inner and outer detectors, with fiducial masses of 0.74 and 0.2 Mton, respectively. In the current baseline design, 99,000 20-inch PMTs will be used for the inner detector, giving a 20% photocoverage. For the outer detector, 25,000 8-inch PMTs will be used. A possible site for the HK tunnel is 8 km south of SK. It has the same off-axis angle with respect to the J-PARC neutrino beam (2.5°) and the same baseline length (295 km) as SK. The rock depth at the site is 648 m (1,750 m.w.e.).

The CP phase will be measured by comparing the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance signals. Assuming that three years of $\nu$-mode data and seven years of $\bar{\nu}$-mode data are collected at a J-PARC beam power of 0.75 MW, the expected reconstructed neutrino energy spectra for $\nu_e(\bar{\nu}_e)$ appearances are plotted in the upper panels of Fig. 7 for various values of $\delta_{CP}$. The lower panels plot the differences from the case of $\delta_{CP} = 0$, including the statistical errors for each bin. These figures show that HK has sufficient statistics to determine $\delta_{CP}$ and to test whether it is consistent with expectations based on the standard 3-flavor oscillation scenario. Figure 8 plots the expected contours for various values of $\sin^2(2\theta_{13})$ and $\delta_{CP}$. Systematic uncertainties of 5% in the $\nu_\mu$ induced background, 5% in the beam $\nu_e$ background, and 5% in the $\nu/\bar{\nu}$ ratio, are assumed. As shown in the figure, HK has sufficiently high sensitivity for $\delta_{CP}$ measurements.

HK is a multipurpose detector, and is capable of detecting a large number of atmospheric neutrino events. Using the zenith angle distribution of multi-GeV electron-like events, the mass hierarchy can be determined. Figure 9 shows its sensitivity for mass hierarchy determination. It can be measured to an accuracy of greater than $3\sigma$ if $\sin^2\theta_{23} > 0.42(0.43)$ for a normal (inverted) hierarchy. Another important goal of HK is to search for proton decay events. For the $p \to e^+\pi^0$ decay mode, the $3\sigma$ discovery potential and the 90% confidence level are $5.7 \times 10^{34}$ years and $1.3 \times 10^{35}$ years for ten years of HK data, respectively. For the $p \to \bar{\nu} + K^+$ decay mode, the corresponding values are $1.0\times10^{34}$ years and $2.5\times10^{34}$ years. For a supernova

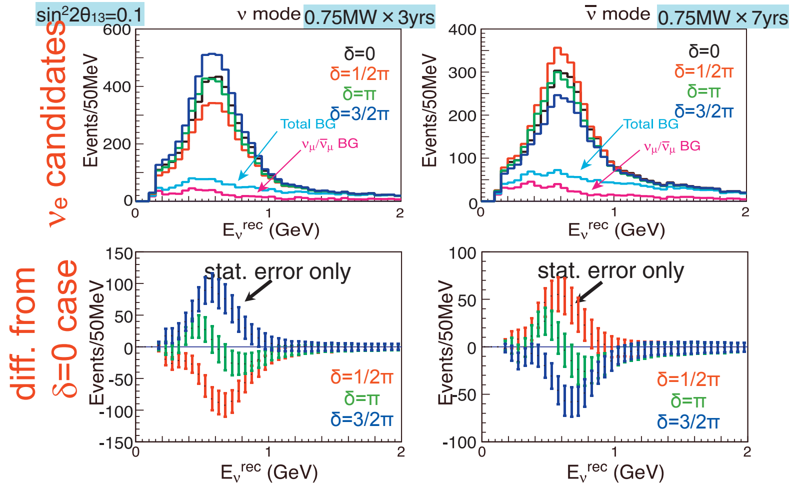


Fig. 7. The upper panels show the reconstructed neutrino energy spectra for $\nu_\mu \to \nu_e$ (left graphs) and $\bar{\nu_\mu} \to \bar{\nu_e}$ (right graphs) for three years of $\nu$-mode and seven years of $\bar{\nu}$-mode data at HK using a 0.75-MW J-PARC beam. The lower panels plot difference spectra from the $\delta_{CP}$=0 case. The errors are purely statistical.

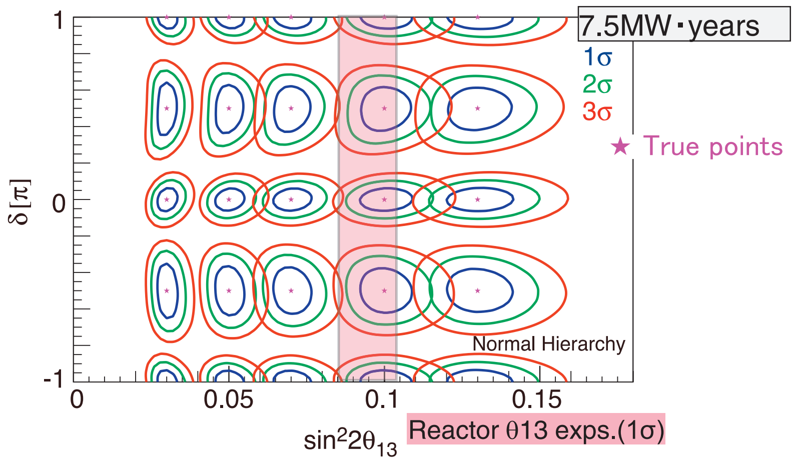


Fig. 8. Expected contours for $\sin^2(2\theta_{13})$ and $\delta_{CP}$ at HK. The blue, green, and red curves are for 1, 2, and 3 $\sigma$, respectively.

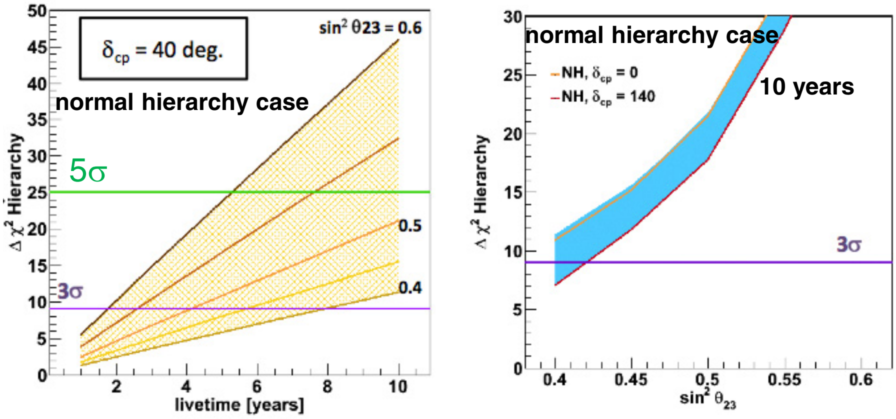


Fig. 9. Sensitivity for mass hierarchy determination using atmospheric neutrinos at HK. The left graph plots the difference in $\chi^2$ between the normal and inverted hierarchies as a function of time for various values of $\sin^2\theta_{23}$, assuming $\delta_{CP} = 40°$. The right graph plots $\Delta\chi^2$ as a function of $\sin^2\theta_{23}$ for a decade of data. The band indicates the range for different values of $\delta_{CP}$.

at a distance of 10 kpc, about 200,000 neutrino events are expected. Even for a supernova at the distance of M31 (the Andromeda Galaxy) 30-50 events are expected. Using the high statistics of galactic supernovae, the explosion process can be investigated in detail. For example, the neutronization burst process, in which electron neutrinos are emitted within about the first 10 ms, can be detected based on just a few tens of events. For SRNs, about 300 events are expected in the energy range of 20-30 MeV for a decade of data, and if Gd is dissolved in the HK tank, the energy spectrum above 10 MeV could be measured based on about 800 events.

## 6. Conclusions

SK has been obtaining data since 1996 and, in addition to discovering neutrino oscillations, it has contributed significantly to measuring various oscillation parameters. SK still has a large amount of potential for physics research, and in the present paper, its prospects over the next decade were presented. Research and development with regard to the SK gadolinium project is ongoing. The T2K experiment has already established that $\theta_{13}$ has a non-zero value, and may provide a hint of non-zero $\delta_{CP}$ in future. In order to determine the actual value of $\delta_{CP}$ and clarify the mass hierarchy, the 1-Mton HK detector is necessary. This is a multipurpose detector that is expected to contribute to both particle physics and astrophysics.

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